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Hydrological evaluation of a peri-urban stream and its impact on ecosystem services potential

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HIGHLIGHTS

- Hydrological and biological evaluation framework in a peri-urban sub-basin.
- Artificial flood control has negative impacts on hydrological integrity.
- Organisms ecological traits can be used as indicators of the ecosystem's condition.
- Natural vegetation and hydro-geomorphology sustain potential HESs provision.

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ABSTRACT

Rivers are aquatic systems with a unidirectional flow. These systems are highly diverse habitats that support a great variety of organisms, which vary in shape and function, and sustain a diverse range of hydrological ecosystem services (HESs). The HESs provided by rivers varies based on complex hydro-geomorphological dynamics and their relationship with the functional processes of the basin. Land use changes in transition zones, where ecosystem functions are compromised, affect the basin, especially basins close to or on the periphery of urban areas. Such is the case for Mexico City, where 60 m^3 of water is consumed per second, 30% of which is imported from outside sources.

The rivers of the Magdalena–Eslava sub-basin are among the few remaining surficial water sources in Mexico City. These rivers are located in an area classified as a Soil Conservation Zone, which has been intensely managed for decades. The aims of this paper are (1) to perform a hydrological evaluation of two urban streams and identify their relationship with the provision of hydrological ecosystem services via (i) a hydraulic balance analysis, (ii) a hydro-geomorphological characterization of each stream, (iii) an estimate of present and potential hydraulic erosion, (iv) the determination of physicochemical and bacteriological parameters and (v) a description of macroinvertebrates, macroalgae and their habitats in order to (2) identify the impacts of socio-economic dynamics on the responses of this rural-urban lotic system. Our results show that water flow, forest cover and hydro-geomorphologic heterogeneity are key to sustaining ecosystem functioning, especially in the high and middle sections of the basin. The highest potential provision of water for direct use was recorded in the sub-basin's middle section; however, the stream channels in that section have lost their natural water flow due to a water management infrastructure built

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to regulate flow during the rainy season. This intervention can be viewed as a regulation of HESs as water management infrastructure alters the transport of sediment and reduces available natural habitat. The provision of quality water in the lower area of the sub-basin has been seriously compromised by the establishment of illegal urban settlements. A relationship between biologically diverse ecological traits and their response capabilities was established and can be considered an indicator of current HES potential. Therefore, this sub-basin may constitute an example of good management and maximizing potential HESs in an urban-rural setting based on improved management strategies that could be applied in other developing nations.

1. Introduction

Rivers are aquatic, temporally heterogeneous systems with unidirectional flow (Kang and Kazama, 2014). These systems can be viewed as complex networks of intersecting primary channels and tributaries (Thorp et al., 2010). Rivers are highly diverse habitats, supporting a great variety of organisms with adaptations that allow them to provide many different ecosystem services (ESs), which benefit humans through direct and indirect effects (MEA, 2005). However, the great majority of rivers in the world are impacted by urbanization, primarily by increased impervious surfaces that alter the hydrological regime (Konrad and Booth, 2005; Walsh et al., 2005), especially in large urban conglomerates such as Mexico City. As a result, the patterns of energy and matter distribution in the local watersheds and their ecosystems have also been altered, both spatially and temporally. These patterns include evapotranspiration, surface runoff, discharge, nutrient availability (nitrogen and phosphorus), soil erosion and sedimentation (He et al., 2000).

Urban development modifies runoff to streams – along with the resulting rate, volume and timing of streamflow – and influences the structure and composition of lotic communities (Miltner et al., 2004; Konrad and Booth, 2005). The flow regime controls aquatic habitat conditions because it is strongly related to the physicochemical characteristics of the stream (Tetzlaff et al., 2005). Other urbanization implications, mainly in low-order streams, include modifications to peak flow, total runoff, stream morphology and water quality, which lead to changes in the input and uptake of nutrients by organisms. The magnitude of these changes is the result of the spatial arrangement of urbanization (Miltner et al., 2004; Jacobson, 2011). Urban streams can be especially impacted by rapid and short-term runoff rates, mainly as a combined result of sewers and storm water overflows (Tetzlaff et al., 2005).

Given these particular conditions, the interaction between ecological and social characteristics should be considered in urban aquatic ecosystems because human interventions can have substantial effects on urban streams and their protection (Walsh et al., 2005). Therefore, the development of a system of readily measurable hydrological and biological indicators, which can describe current stream conditions, the health of the watersheds and associated water resources, is essential for their protection and sustainable use (He et al., 2000). Appropriate indicators can be used to track environmental modifications and their effects on ES provision and human health, and they can provide support for strategic planning initiatives and proposed freshwater policies and best management practices (He et al., 2000).

The ES concept has become increasingly used due to an increase in ecosystems management. This concept makes tangible the relationship between ecosystems and the services they can provide, revealing a direct relationship between the natural world and human well-being (Dobbs et al., 2014). Ecosystem services are classified in accordance with the Millennium Ecosystem Assessment (MEA) into four large groups: provision, regulation, cultural and support.

The provision capacity of hydrological ecosystem services (HESs) is highly dependent on the hydro-geomorphological characteristics of a basin as well as its biodiversity. Provision also depends on the existence of stochastic physical disturbances, the stability of habitat conditions and their influence on ecosystem functions (Benda et al., 2004).

In a lotic system, gradual change in the characteristics downstream has an impact on the biological assemblages present and, in turn, on the capacity of ESs (Thorp et al., 2010; Larondelle and Haase, 2013).

Because the majority of urban landscape components are complex and strongly interconnected with adjacent ecosystems, change in land use along the river system in the transition zone between ecosystems in urban basins can affect functional processes (Radford and James, 2013; Lauff et al., 2014; Dobbs et al., 2014).

Knowledge of how landscape structure and socio-demographic traits are related to ES capacity has increased in the last decade. This information has helped urban planners and policy makers to guide city growth and development plans (Dobbs et al., 2014; Lauff et al., 2014; Larondelle and Haase, 2013). In cities where ES capacity is provided by rivers, particularly in developing countries, ES capacity has been greatly reduced due to inadequate or excessive water management (Jujnovsky et al., 2012). Therefore, having a baseline of the existing spatio-temporal state of hydrological and biological conditions constraining ES capacity on a local or regional scale becomes important for planning for environmental and cultural sustainability (Lauff et al., 2014). Urban areas have been able to expand considerably in recent years, largely due to the application of the ES concept, which is enabling these urban areas to achieve local ecosystem independence. The Mexico Basin serves as an example of the potential down-river impacts of urbanization. The basin consumes 77 m^3/s of water, of which 71% comes from groundwater, 2% from springs and surficial water sources and 27% from the Lerma–Cutzamala Basin, which is located over 100 km from the city (Mazari-Hiriart et al., 2014). Among the few surficial water sources in the Mexico Basin are the rivers of the Magdalena–Eslava sub-basin, which was used in this study as a model to identify hydrological and biological changes in a rural–urban setting and the relationship of these changes to potential HES capacity. Studies to determine water availability have been conducted in this area previously (González-Martínez, 2008; Jujnovsky et al., 2012). Therefore, our aim was to improve knowledge related to other hydrological sources and their spatial location. The hypothesis of this study is that zones with lower anthropogenic influences in the Magdalena–Eslava sub-basin and within the Mexico Basin have experienced less dramatic hydrological changes, which will be reflected in the biological composition and HES potential of the studied streams. With this in mind, this study aims to (1) describe the spatial distribution of hydrological and biological conditions resulting from land use-cover changes across the study sub-basin and their relationship with ecosystem services potential, using the following indicators: (i) hydrological balance analyses; (ii) hydro-morphological characterization; (iii) present and potential hydraulic erosion estimation; (iv) physical–chemical and bacteriological parameter determination; and (v) macroinvertebrate, macroalgae and habitat descriptions in order to (2) identify the impacts of socio-economic dynamics and the potential of ecosystem services on hydrologic resources in a rural–urban setting.

2. Study area

In recent decades, Mexico City has dramatically increased its dependence on the supply of natural resources, exceeding the limits of sustainability. Nevertheless, the city has 87,000 ha of natural areas designated as ''Federal Soil Conservation Districts'' (CS), which are mainly mountainous, forested regions that provide fundamental ESs to the city inhabitants (Jujnovsky et al., 2012). The best preserved sub-basins are located in the southwest region of the basin and are represented by the Magdalena–Eslava River sub-basin (PUEC-UNAM-GDF, 2008; UAM-GDF, 2008). The sub-basin has a dendritic geometry, is located in the morpho-tectonic region of the Trans-Mexican Volcanic Belt at minimum extreme coordinates 463 915; 2 126 293 and maximum extreme coordinates 475 774; 2 134 715, and has a total surface area of 50 km^2 (Ferrusquía-Villafranca, 1998). The Magdalena River originates at an elevation of 3650 masl and extends 28.2 km to the edge of the Mexico City urban zone at 2300 masl. The river then runs for 14.8 km through the CS area. The Eslava River, the main tributary of the Magdalena, originates at an elevation of 3557 masl and extends 13.4 km to its confluence with the Magdalena, just as it enters the urban soil area at km 15. The two rivers provide 1% of the local surface water supply of Mexico City (Mazari-Hiriart et al., 2014). The region is important for its historical, religious and cultural heritage, and the sub-basin features weekend tourism, sports and religious activities, all within an agricultural and silvo-pastoral setting.

The region has a sub-moist temperate climate with a median annual temperature of 13.4 °C. Rain is abundant from June to October, with a median annual precipitation between 1200 and 1500 mm, and the dry season runs from November to May (García, 2004). Geological traits consist of rock outcrops of alternating andesitic and basaltic lavas (Ferrusquía-Villafranca, 1998). Forests of *Abies religiosa* (Kunth) Schltdl. and Cham., *Pinus hartwegii* Lindl. and *Quercus* spp. grow in the upper zone of the watershed, with mixed forest in the mid- and lower regions (Ávila-Akerberg, 2010). To identify the hydrological and biological conditions and HES capacity of the basin, we selected four sampling sites along the Magdalena River (M-CS) and three sites along the Eslava River (E-CS), all within the CS. These sites were also selected because previous studies have looked at these sites and provide supporting data for the information presented here (PUEC-UNAM-GDF, 2008; UAM-GDF, 2008; Mazari-Hiriart et al., 2014; Caro-Borrero et al., in press).

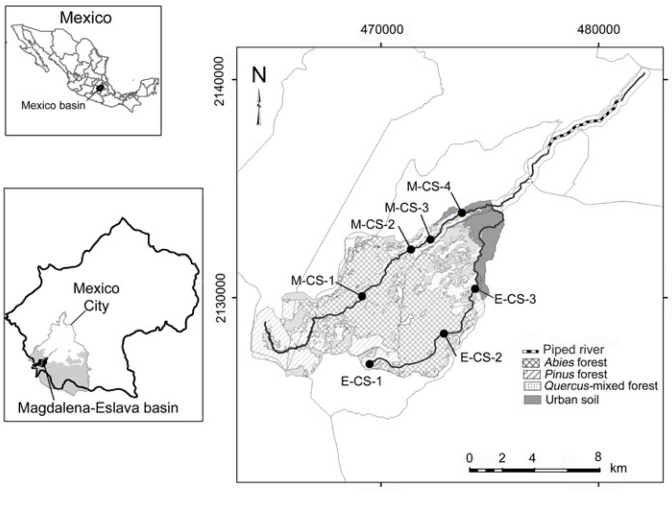

Fig. 1. Location of sampling sites in the Magdalena–Eslava River sub-basin, Mexico Basin. M-CS, Magdalena soil conservation; E-CS, Eslava soil conservation. Area coverage by land use type as described in Table 2.

3. Methods

Selection of hydrological and biological indicators was driven by availability of data within the study area at a local scale and their relationship with HES potential (Table 1). All of the selected indicators were considered of priority interest for the conservation and HES support of cities and peri-urban zones (Radford and James, 2013).

Table 1
Criteria used to evaluate hydrological and biological changes and HES potential in the Magdalena–Eslava sub-basin.

Indicator	Method	Data source
Local climate interactions and water use: potential provision services		Digital elevation model (INEGI, 2000)
Water quantity	Soil Water Assessment Tools (SWAT) (Neitsch et al., 2002)	Soil cover and hydrologic network (Ávila-Akenberg, 2005)
Soil and riverbank development, surface flow, chemical and biological additions/subtractions: regulation of ecosystem services		Soil type (RAN, 2000) Hydrologic network (Ávila-Akenberg, 2002) Climate (ERIC III, 2014)
Sediment transport regulation—Fluvial geomorphology	Maximum and minimum floodplain (Rosgen, 1996)	Local weather data (Dobler, 2011)
	Riverbank and water mirror (Rosgen, 1996)	Hydrometric records (DGCOH, 1999)
	River course type (stretch, sinuosity, width/deepness and slope index) (Rosgen, 1996)	Soil type and texture (FAO, 1980)
Hydrologic erosion	Universal Soil Loss Equation (RUSLE) (Renard et al., 1997)	Land use and Vegetation type-C factor (SEDUSU) Rain erosion map-R factor (Cortes, 1991)
Water quality regulation	Physicochemical parameters recorded *in situ* Discharge flow (Gore, 1996) Ammonium nitrogen, nitrate nitrogen, total nitrogen orthophosphates, and total phosphorous were analysed in triplicate using a spectrophotometer HACH Model DR2400 (Loveland, CO, USA) following the HACH manual (APHA, 2005; HACH, 2003) Faecal coliforms and faecal enterococci (DOF, 1994; APHA, 2005)	Mean annual precipitation-K factor (FAO, 1980) Terrain slope and slope projected length (LS factor) (Renard et al., 1997)
Biodiversity: supporting ecosystem services		
Habitat diversity and organisms	Shannon Wiener index-H′ (Magurran, 2004)	
Macroinvertebrate sampling	Multi-habitat criterion (Bennett et al., 2011)	
Macroalgae sampling	Quadrat method (Necchi et al., 1995)	

3.1. *Local climate interactions and water use: potential provision services*

Water quantity (WQ). WQ is defined here as the volume of water that can be directly extracted from a water source for human use. In this study, WQ was measured as the balance between the directly extracted water and the base runoff. To calculate this balance, the following equation was used:

$$\mathrm{WB} = \mathrm{P} - \mathrm{Et} - \mathrm{Ro} - \Delta\,\mathrm{SM}$$

where

WB: water balance
P: precipitation
Et: evapotranspiration
Ro: runoff (surface runoff + base flow + water recharge of the confined aquifer)
Δ SM: change in soil moisture.

Hydrological modelling relied on SWAT (Soil Water Assessment Tools), with the AvSWAT interface for Arc-View 3.2 (Neitsch et al., 2002). A paired basin hypothesis was generated based on previous modelling conducted in the Magdalena River sub-basin (González-Martínez, 2008; Jujnovsky et al., 2012). This model was selected because it allows data to be compared at different scales. Splitting a sub-basin into smaller sub-basins of arbitrary size, called runoff units, can be based exclusively on hydrological information. These sub-basins in turn can be further divided into hydrologic response units that are influenced by two qualities determined, in part, by hydrologic behaviour: land use and land cover (Neitsch et al., 2002). The model's response variables are precipitation, soil water content, present and potential evapotranspiration, surface runoff, subsurface runoff, percolation and water yield production. This information was analysed in the context of the type of forest cover present in the sub-basin and how that cover affects each of the response variables.

3.2. Soil and riverbank development, surface flow, chemical and biological additions/subtractions: regulation of ecosystem services

Sediment transport regulation—Fluvial geomorphology. This evaluation assesses the balance among erosion, transport, and deposition of sediments in a section of the river, which can also determine potential habitats of river organisms. At each sampling station, a 100 m transect was established and topographic data were collected as described by Rosgen (1996).

Hydrologic erosion control. This action refers to the prevention of soil loss and increased retention on the flood plain. Water availability and nutrient cycling; dead organic matter, including human waste; processing; and conservation of system fertility are also involved. Present and potential hydraulic erosion modelling was conducted using inputs from rain erosion maps; local weather data; rain erosion factor (R factor) isohyet maps that represent mean annual precipitation, soil type and texture (K factor), land use and vegetation (C factor); and terrain slope and slope projected length (LS factor). The L factor refers to the varying length obtained through this equation (Renard et al., 1997).

Water quality regulation. This function measured the factors outside the river system that alter the quality of water, including noxious organisms that affect human health. Sampling was performed four times between September 2012 and September 2013 – twice in the rainy season, once in the dry cool season and once in the dry warm season – following the parameters established by the Official Mexican Norm (DOF, 1994). Physicochemical parameters were recorded *in situ* using a YSI 6600 Multi-parameter probe (Yellow Springs, OH, USA). These parameters included water temperature, electrical conductivity (K_{25}), dissolved oxygen (DO), pH and discharge flow (Q3 $m^3\ s^{-1}$).

At each sampling station, 500 mL water samples were collected in sterile polypropylene bottles for the physicochemical analysis using criteria established by the official Mexican guidelines and international technical guidelines (DOF, 1994; APHA, 2005). One-litre samples were collected in sterile polypropylene flasks stored at 4 °C for bacteriological analysis. Processing occurred within 24 h of collection using the membrane filtration technique (DOF, 1994; APHA, 2005).

3.3. Biodiversity: supporting services

Habitat diversity and organisms. The evaluation of habitat diversity related the spatial heterogeneity of the sub-basin to river organism diversity. Biodiversity was estimated using the Shannon Wiener index (Magurran, 2004). Macroinvertebrate and macroalgae (particularly those with conspicuous macroscopic growth (macroalgae, *sensu* Sheath and Cole (1992))) abundance was obtained through four collection field trips over one year (refer to Section 3.2).

Macroinvertebrate sampling. At each sampling location, collection points were selected following a multi-habitat criterion (Bennett et al., 2011). Samples were collected along 50-m transects. Sediment was removed over 10 min, and macroinvertebrates were sorted from sediments in a tray over three minutes. Capture was also performed via manual examination of the submerged faces of large rocks, branches, and leaves; macroinvertebrates were manually removed until a minimum of 100 individuals were collected from each location as a representative sample.

These samples were preserved in 96% alcohol. Macroinvertebrate individuals were sorted and identified using an Olympus SZX7 stereoscopic microscope (Olympus Corporation, Tokyo). Specimens were identified to genus when possible using a specialized bibliography (Dewalt et al., 2010; Merritt et al., 2008).

Macroalgae sampling. The macroalgae community assessment was performed along the same 50-m transect selected to sample macroinvertebrates. The segments were divided into ten equal parts and contained typical microhabitats. The abundance of macroalgae (cover percentage) was evaluated with a circular sampling unit of 10-cm radius (Necchi et al., 1995). Measurements were performed over natural substrate (rocks) directly on the riverbed. For taxonomic analyses of cytological characters, an Olympus BX51 microscope with an SC35 Microphotography System was used.

4. Results

4.1. Local climate interactions and water use: potential service provisions

Water ES: The hydrologic balance by land use type presents values weighted by the area covered (Table 2). Water yield in the Magdalena River hydrologic network comes primarily from *Abies religiosa* forests and secondarily from *Pinus hartwegii* forests found in the upper and middle sections of the sub-basin. *Abies religiosa* forests cover the higher elevations and supply most of the water for the Eslava River (Fig. 5(d)). The component of the water balance with the lowest values was deep infiltration.

Table 2
Hydrologic balance components of the Magdalena–Eslava sub-basin modelled using SWAT.

Magdalena river (cover type)	SWAT sub-basin's division	Area (km^2)	Ppt	EPT-A	BASE	WYLD
Quercus and mixed forest	6	2.395	78	48	34	40
Abies religiosa forest	20	16.133	582	373	270	325

(continued on next page)

Table 2 (*continued*)

Magdalena river (cover type)	SWAT sub-basin's division	Area (km^2)	Ppt	EPT-A	BASE	WYLD
Pinus hartwegii forest	19	9.248	375	214	165	211
Grassland	4	0.912	36	25	21	19
Urban	4	1.104	36	20	9	19
Total	53	29.792	1107	680	499	614
Eslava River						
Quercus and mixed forest	6	4.038	195	121	91	104
Abies religiosa forest	10	13.478	702	417	323	397
Shifting cultivation (crop rotation)	8	2.389	111	77	45	58
Urban	13	2.098	104	52	27	60
Total	37	22.003	1112	667	486	619

Ppt: precipitation; EPT-P: potential evapotranspiration; EPT-A: actual evapotranspiration; GW_Q: subterranean runoff; WYLD: total water yield; BASE: base runoff (lateral and groundwater runoff). Data are shown in mm.

The greatest potential for water balance ES was observed at stations located in areas of pine and oak-pine forest within the sub-basin. These stations cover the upper section of the sub-basin (M-CS-1 and E-CS-1) and the lower section of the Eslava River, which contains *Quercus* and mixed forests (E-CS-3). Intermediate zones offer lower potential water balance ES values. However, these zones are where most of the human activities in the region are concentrated, including trout farms, Christmas tree plantations, agricultural activities, and tourist attractions. Very low potential ES values were observed at point M-CS-4, likely due to greater land use for agriculture, illegal urban settlements, and a water treatment plant with a capacity of 200 L s^{-1}.

4.2. Soil and riverbank development, surface flow, chemical and biological additions/subtractions: regulation of ecosystem services

Sediment transport-fluvial geomorphology. The first- to third-order rivers in the study area have pronounced slopes: semi-straight (index value of 1–3), slightly sinuous (value of 1), or moderately sinuous (index values of 1.3–2) (geomorphology, Table 3). The transverse sections of the Magdalena River (Fig. 2(a)–(d)) were wider and shallower and exhibited greater flow values, with an average of 0.4 m^3 s^{-1} and maximum of 1.06 m^3 s^{-1} (M-CS-3) recorded during the warm rainy season and a minimum of 0.01 m^3 s^{-1} (M-CS-3) recorded in the warm dry season.

The Eslava River cross-section stations show that the rivers are fed by many shallow springs during low flows, which develop into the main river downstream (Fig. 2(f)–(h)). The lower reaches are fed by narrow, weaker flowing streams averaging 0.005–0.03 m^3 s^{-1}. The highest flow was observed during the warm rainy season (0.06 m^3 s^{-1}; E-CS-3) in the lower sub-basin. Minimum flow was observed during the cold dry season at the river source and averaged 0.002 m^3 s^{-1} (E-CS-1).

Following Rosgen's (1996) classification, four types of streams were differentiated in the sub-basin: Aa^+, A, B and C (Table 2). The Aa^+ type is a typical headwater stream, where waterfalls and plunge pools are common. These channels are very narrow and are characterized by significant erosion and transport capacity downstream. Class A streams are steep mountain rivers with narrow, confined channels. These streams have waterfalls, high flows and erosion and a limited supply of sediments (e.g., points M-CS-1 and E-CS-1). Class B streams are moderately narrow and less steep than Class A streams. Their riverbeds are relatively stable and have a limited supply of sediments (e.g., points M-CS-2, M-CS-3, E-CS-2 and E-CS-3). Class C streams are more broad than deep, with well-developed alluvial plains. These streams are stable, with limited ability to transport sediments. Sediment deposition occurs along the bed and banks, though a large percentage remains suspended in the water column. M-CS-4 on the Magdalena River was classified as a Class C stream.

Table 3
Stream classification and fluvial typology in the Magdalena–Eslava River sub-basin (after Rosgen, 1996).

Key sites /altitude m a.s.l.	Soil cover	River order	Narrowness index	Sinuosity index	Width/depth index	Slope index	Description	Type
Magdalena River Conservation Soil (M-CS-)								
M-CS-1 3099	Sacred fir forest (*Abies religiosa*)	2	0.75	1.16	16.25	1.477	Steep slope; tight, erosive streams with large rocks or material.	Aa^+
M-CS-2 2727	*Quercus* forest	3	0.75	1.84	15.94	1.86	Moderate slopes; narrow valleys with steep hillsides. Very stable riverbanks and flood plains.	B
M-CS-3 2698	*Quercus* forest	3	0.88	1.31	16.02	1.62		B

(*continued on next page*)

Table 3 (*continued*)

Key sites /altitude m a.s.l.	Soil cover	River order	Narrowness index	Sinuosity index	Width/depth index	Slope index	Description	Type
M-CS-4 2591	Degraded mixed forest	3	0.97	1.22	55.55	1.29	Streams with mild slopes; fine sediment deposition zones, fluctuation between river rapids and pools.	C
Eslava River Conservation Soil (E-CS-)								
E-CS-1 3557	Pine forest	1	0.93	1.22	3.23	0.52	Marked topography alternating erosion and deposition zones. Confined stream with waterfall reaches.	A
E-CS-2 2965	Sacred fir forest (*Abies religiosa*)	1	0.86	1.01	21.61	1.92		B
E-CS-3 2769	*Quercus* forest	2	0.53	1.06	6.31	3.21		B

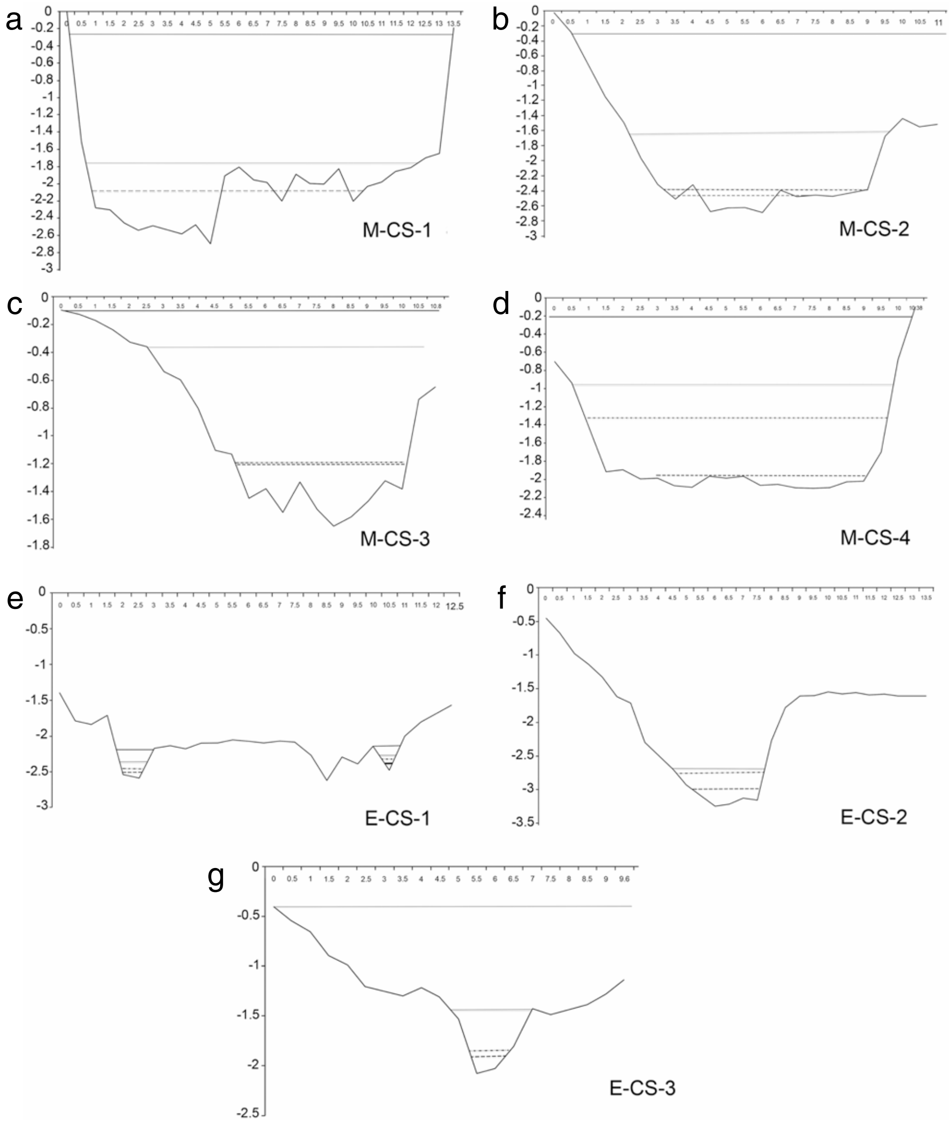

Fig. 2. Cross-sections of the Magdalena River (a–d) and Eslava River (f–g). The black solid line is the maximum extent of flooding. They light grey line corresponds to the minimum flow levels. The dot-dash line is the riverbank and the dashed line is the water mirror. Axis units are in metres.

Water quality control. According to the Mexican Official Norm for human water consumption, water in the lower reaches of the sub-basin (M-CS-4 y E-CS-3) is unfit for human consumption because it exceeds allowable total phosphorus and faecal coliform concentrations (NOM-127-SSA1-1994) (DOF, 1994) (nitrate nitrogen 10 mg L^{-1}, ammonium nitrogen 0.5 mg L^{-1}, total phosphorus 0.2–0–5 mg L^{-1}, and faecal coliform 0 UFC/100 mL). CFU (faecal coliform concentrations) increased exponentially downstream (Fig. 3). As such, the radius of enterobacteria was chosen as a reference (Toranzos et al., 2007) (Fig. 5(b), Table 4). In all sampled sites, the FC/FE radius shows that contamination comes mainly from animal sources (0.7–2) (Fig. 5(a)). This water quality pattern was also indicated by macroinvertebrate biodiversity and contamination tolerance and algal taxa, the numbers of which are notably reduced at the sites with greatest human influence (Fig. 5(c)).

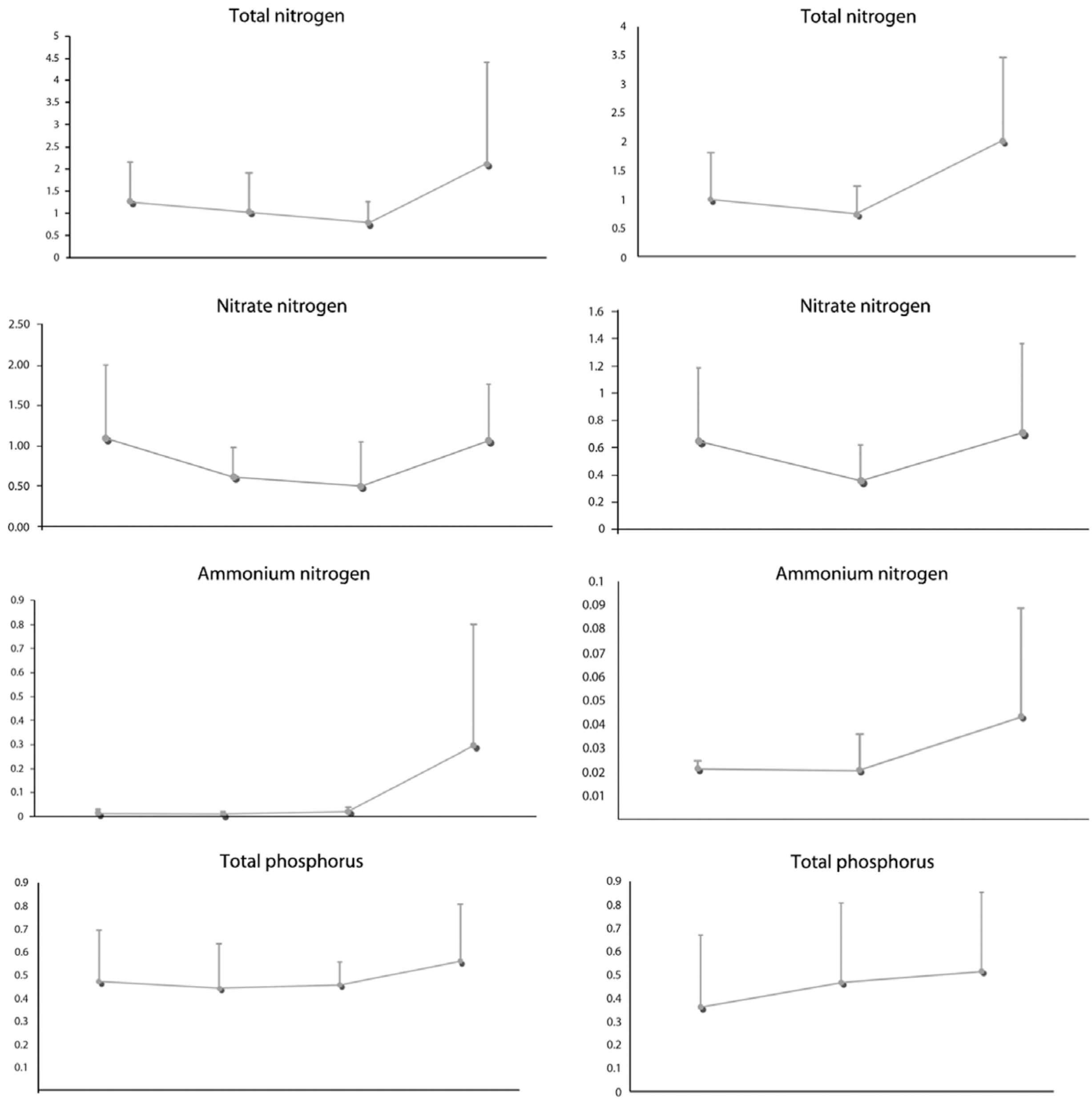

Fig. 3. Total nitrogen, nitrate nitrogen, ammonium nitrogen, total phosphorus, orthophosphate, faecal coliform bacteria and faecal enterococci (n: 1 6, mean ± SE) for the sample stations studied. Figures corresponding to the Magdalena River data are on the right, and those corresponding to the Eslava River are on the left. Site abbreviations correspond to those shown in Fig. 1.

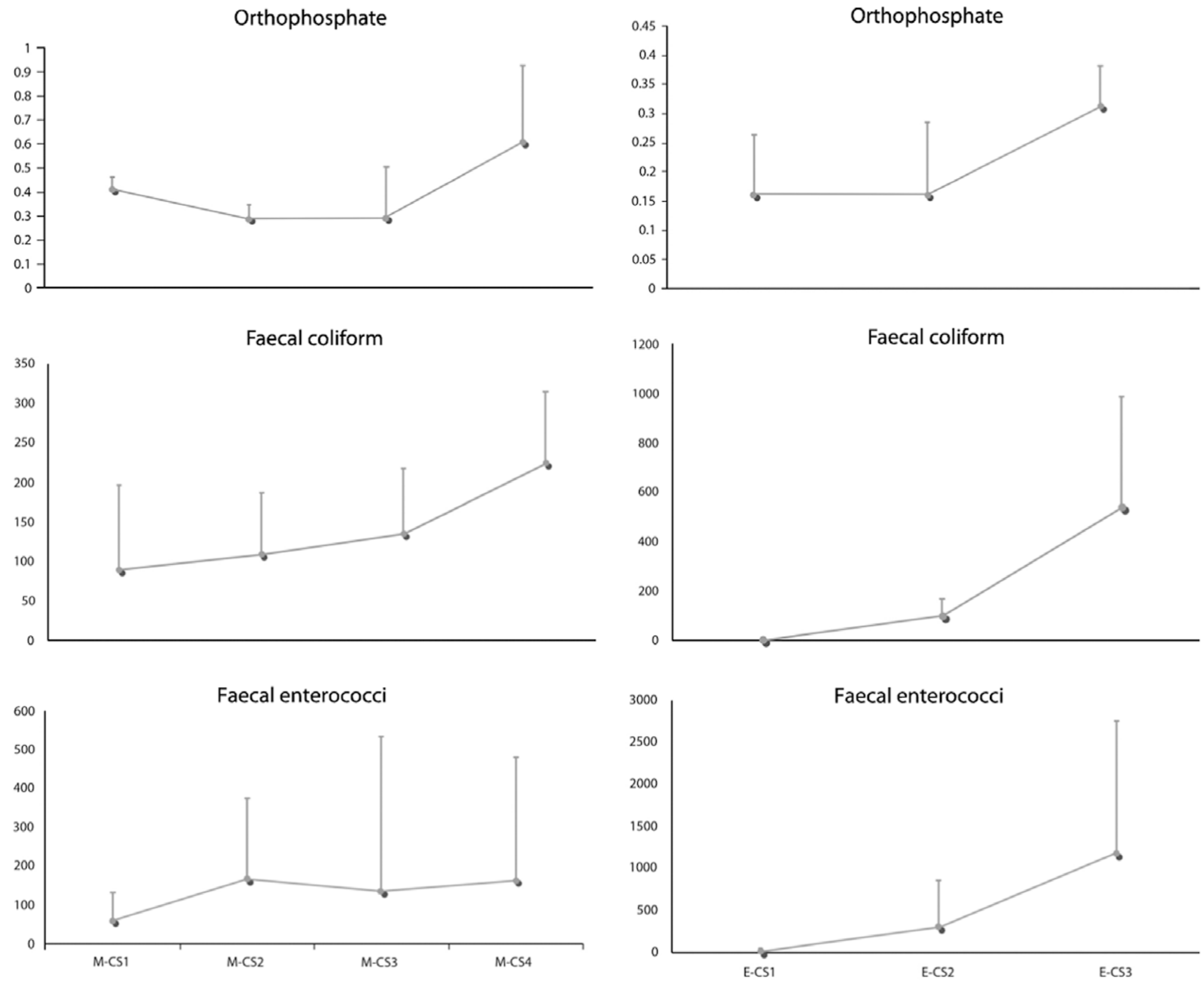

Fig. 3. (*continued*)

Hydraulic erosion control. The low erosion values (less than 50 ton/ha/year) for the sub-basin are likely due to the area's well-preserved forest setting. The highest recorded values ranged from 50 to 200 ton/ha/year and were found in downriver zones with hydraulic structural modifications (mainly agricultural land use and illegal urban settlements) (Fig. 4(a)). The potential erosion scenario that would result from the removal of native vegetation shows that if such land use change continues, values will range from 200 to 1200 ton/ha/year (Fig. 4(b)).

4.3. Biodiversity: supporting ecosystem services

Habitat diversity and organisms: We identified 29 benthic macroinvertebrate taxa in this study: *Acarina*, Anomalopsychidae, *Baetis* (Baetidae), Tanypodinae, Orthocladiinae, Podonominae (Chironomidae), Dixidae, *Dytiscus* (Dytiscidae), Elmidae, Empididae, Ephemerellidae, *Glossosoma* (Glossosomatidae), *Epeorus* (Heptagenidae), *Atopsyche* (Hydrobiosidae), *Hydropsyche* (Hydropsychidae), Hydroptilidae, Leptoceridae, *Hesperophylax, Limnephilus* (Limnephilidae), *Nemouridae*, Oligochaeta, Planariidae, *Polycentropus* (Polycentropodidae), Psychodidae, *Simulium* (Simuliidae), Stratiomyidae, *Tipula, Antocha* (Tipulidae) and Veliidae. We identified eight species of macroalgae: *Placoma regulare* and *Nostoc parmelioides* (Cyanobacteria); *Vaucheria bursata* (Heterokontophyta); *Prasiola mexicana, Ulothrix* sp., *Oedogonium* sp., *Spirogyra* sp. and *Cladophora* sp. (Chlorophyta). The diversity ($H' = 1–1.5$) and equitability (0.5) values are similar among stations, with a slight tendency to increase in zones near the city limits and to decrease near headwaters (as recorded at the source of the Eslava River (E-CS1)).

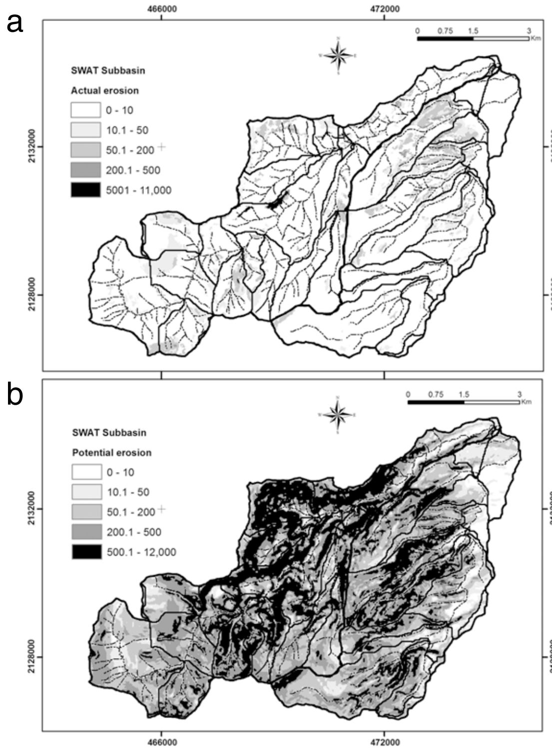

Fig. 4. Actual and potential erosion models in the Magdalena–Eslava River sub-basin. The sub-basin's spatial division was generated using SWAT. (a) Actual hydraulic erosion in ton/year. (b) Potential hydraulic erosion in ton/year.

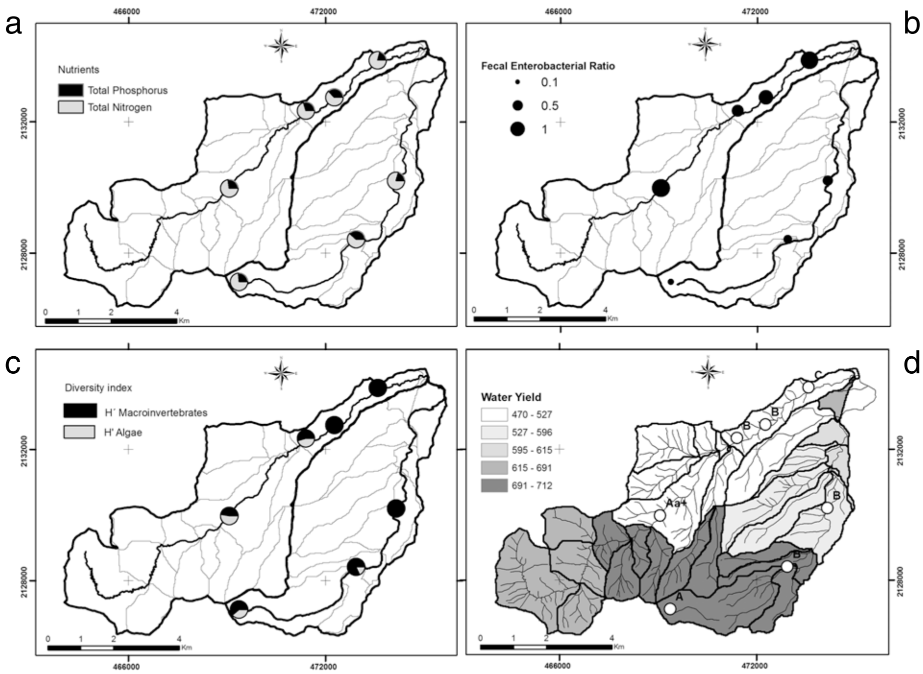

Fig. 5. Map compositions using hydrological and biological indicators in the Magdalena–Eslava Rivers sub-basin. SWAT modelling divisions of the sub-basin are shown. (a) Proportional concentration of total phosphorus and nitrogen in mg L^{-1}; (b) faecal coliform and enterococci radii (interpretation values in Table 4); (c) proportion of macroinvertebrate and macroalgae diversity; (d) total water yield in mm/year, letters correspond to Rosgen's (1996) classification (detailed description in Table 2).

5. Discussion

Since the beginning of the last century, the Magdalena–Eslava sub-basin has been subjected to intense hydraulic and forest management. For nearly 50 years, the sub-basin was the main energy source of textile industries and the watershed was the source of wood for paper industries in the area. Aquatic communities have had to adapt to the drastic changes in the sub-basin, from a rural zone with industrial activity to a rural–urban transition zone dominated by urban land use that has included structural modifications to the channel, in only a few decades. Rivers are stochastic environments where changes in water flow are the main source of natural variation. However, human activity can establish chronic variation to which existing biological communities are not adapted (Dewalt et al., 2010).

Controlling and halting urban growth within the sub-basin is one of the greatest challenges facing decision makers. When the range of impervious cover within a watershed reaches 8%–20%, the hydrological and geomorphological consequences grossly impair biological communities (Miltner et al., 2004). Currently, and despite the fact that the sub-basin is supposed to be protected as a CS, 14% of the land is urban; the effects are visible in the hydrological behaviour as well as the diversity and composition of macroinvertebrate and macroalgae communities in the downstream section.

Despite the intense historical exploitation of these rivers and present human activity, the analysis of hydrological and biological features in the Magdalena–Eslava sub-basin, along with their consequent HES potential, indicate that elements such as water flow conservation, riparian vegetation and hydro-geomorphologic heterogeneity are key components in the recovery of stream functionality.

5.1. Local climate interactions and water use: potential for the recovery of HESs

Water quantity: The analysis of vegetation types throughout the sub-basin indicates the importance of the relationship between the composition and structure of plant communities and the hydrological processes that facilitate the regulation of water flow. Vegetation is often the driving force of ecosystem effects on water (Brauman et al., 2007). For example, forests of *Abies religiosa* and *Pinus hartwegii* are vital for water infiltration, storing water that can be used to support biological communities and human uses. However, the lower sub-basin, where *Quercus* spp. and mixed forests are found, has been heavily impacted by human activity. These impacts ultimately affect the rivers' ability to provide a sufficient quantity and quality of water (Brauman et al., 2007; Yapp et al., 2010; Radford and James, 2013; Mazari-Hiriart et al., 2014). The extent of the impervious surfaces within the sub-basin also influences differences in water production between the rivers and is related to on-going water extraction. Young and invasive plants generally have disproportionately large impacts on water quantity because vigorously growing vegetation tends to use more water than mature vegetation (Brauman et al., 2007).

Past studies evaluating water provision as an ES of the sub-basin showed that, in the period between 1990 and 2010, the natural water flow was altered in order to be controlled. This process promoted a reduced flow due to the retention and storage of water. This trend was recorded by Mazari-Hiriart et al. (2014) from 1999 to 2001, where the mean flow values were 0.70 $m^3\ s^{-1}$ (21,771,800 $m^3\ y^{-1}$) and 0.67 $m^3\ s^{-1}$ (21,538,250 $m^3\ y^{-1}$) between the years 2002 and 2003 and 0.59 $m^3\ s^{-1}$ (18,400,000 $m^3\ y^{-1}$) in 2012 (Jujnovsky et al., 2012). The average flow values recorded in the present study, 0.6 $m^3\ s^{-1}$ (18,292,288 $m^3\ y^{-1}$), are consistent with those reported by Jujnovsky et al. (2012) and equivalent to values for the Magdalena River and in the Eslava River (0.44 $m^3\ s^{-1}$; 13,619,857 $m^3\ y^{-1}$). Variations in the data may be explained by local climate interactions, which can either increase or decrease available water; natural factors, such as changes in precipitation and temperature patterns that may have increased the evapotranspiration volume in a particular region; and alterations of the flow dynamics caused by an artificial drainage system characterized by the flashy and short-term responses of combined and storm sewer overflow (Tetzlaff et al., 2005). Although water production seems to have remained stable, the construction of gabion dams in the headwaters to control flow (Mazari-Hiriart et al., 2014), together with land use changes, pose a potential risk to water flow stability. At present, there are 90 dams on the Magdalena River and 83 on the Eslava River. These dams are fragmentation structures that have altered the upstream section of the sub-basin.

According to Jujnovsky et al. (2012), the present water supply in the sub-basin serves 32,273 inhabitants, with 153,203 potential beneficiaries in its area of influence. Beyond being used for drinking water by the sub-basin's 32,273 inhabitants, supplying water to potential beneficiaries represents a source of income for local inhabitants. This water supply also helps to provide income to local inhabitants through tourism (e.g., restaurants along the river that make direct use of the water) (Neitzel et al., 2014). Water is primarily drawn directly from the rivers, as groundwater infiltration is negligible due to the morphological and geological characteristics of the sub-basin.

Water quantity is the first attribute of a water service many people consider, but for services such as water supply, an increase in quantity is beneficial, whereas in flood mitigation, a decrease in quantity is beneficial (Brauman et al., 2007). Based on the water balance in the Magdalena–Eslava sub-basin, maintaining flood regulation and water provision requirements necessitates better management of water during the rainy season.

5.2. Soil and riverbank development, surface flow, chemical and biological additions/subtractions: regulation of ecosystem services

Sediment transport: sediment transport has been altered by hydraulic structures in the upper section of the sub-basin (Mazari-Hiriart et al., 2014). Structural modifications in the upper sub-basin likely affect the role of riparian areas in influencing the river's ecological processes. For example, water supply, water flow, sediment, and driftwood to small tributaries have been reduced by dams. This change results in reductions of organic matter accumulation and physical habitat heterogeneity (Benda et al., 2004; Thorp et al., 2010). The minimum stream size needed to maintain a healthy riparian ecosystem will also be altered.

Modifications using hydraulic structures help to protect human populations by reducing current speed and sediment yield downstream. However, the high density of structural modifications can reduce the channel size to below the minimum size required to maintain a healthy riparian ecosystem. Enterobacteria values obtained from water samples reveal that animal herding conducted near to or directly crossing the river contributes to an increase in sediments and a decrease in bank stability (Wohl, 2006). In the lower reaches of both rivers, the transport of sediment and organic matter has a cumulative effect; upstream modifications, illegal urban settlements, agriculture, and runoff from dirt roads combine to have a greater impact downstream. All of these factors further increase sediment yields, altering the riverbed and bank stability (Wohl, 2006). Therefore, it is necessary to reduce the number of hydraulic structures that control river flow (e.g., gabion dams and percolation trenches) and regulate activities that cause the loss of riparian vegetation and habitat (Kang and Kazama, 2014).

Water quality: Faecal enterobacteria radii have serious limitations due to different die-off rates of the two groups of bacteria. However, the samples indicated that water contamination occurred mainly from animal sources and that the influence of human settlements upstream and in the middle section of the sub-basin were weaker than downstream. Vegetation and intact groundcover and root systems are effective at improving water quality (Brauman et al., 2007); in the Magdalena–Eslava sub-basin, the vegetation and root systems were altered by water retention ponds constructed to prevent flooding downstream. The improved water quality conditions are also related to better vegetative and morphological sub-basin conditions.

Phosphorus enrichment and an increase in enterobacteria numbers are likely related to aquaculture and pastoral activities—mainly trout farming, which has an important effect on nutrient enrichment through the alteration of the composition and structure of benthic aquatic communities (Merritt et al., 2008).

The distribution and abundance of nutrients also play important roles in biotic interactions, which can be seen in the heterogeneous composition of macroalgae and macroinvertebrate communities. The presence of *Nostoc parmelioides* and *Placoma regulare* in the headwaters reflects their ability to fix atmospheric nitrogen and accumulate phosphorus in nutrient-poor aquatic environments. In addition, nutrient enrichment can explain the presence of species tolerant to riparian vegetation loss and water quality alteration. Examples of these taxa include Tanypodinae, Oligochaeta and *Dytiscus* benthic macroinvertebrates (Merritt et al., 2008). Nutrient enrichment can also explain the presence of tolerant macroalgae, such as *Prasiola mexicana*, that are also sensitive to stream flow (Bojorge et al., 2010).

Water quality may be regulated by organisms through the biochemical transformation of nutrient-enriched water. Such organic contamination-tolerant macroinvertebrates and macroalgae provide important ESs (Brauman et al., 2007; Thorp et al., 2010; Quijas and Balvanera, 2014). An example of this effect is the reduction in water-transmitted pathogens because of the diversity of filtering organisms such as *Distycus*, *Polycentropus* and Empididae.

Water quality can also influence other ESs, such as recreation, arable land irrigation, food supply through trout farms, and ecotourism. The absence of regulation of these activities is detrimental to the preservation of water quality. Water quality is also impacted by gabion dams and their related effects on nutrient retention and the "self-cleaning" dynamics of the sub-basin (Jujnovsky et al., 2010; Mazari-Hiriart et al., 2014; Caro-Borrero et al., in press).

Hydraulic erosion control: In general, the sub-basin is characterized by lower temperatures, steeper slopes, and faster currents. As the river descends to lower reaches, temperatures rise and the slope flattens and reduces the current's speed. Throughout the basin, current velocity is the major physical agent shaping the topographical profile and determining the type and size of sediment in a given reach. The zones with greater erosion correspond to areas of land use change, where elements such as urbanization, agriculture and tourism are present. Currently, 3.202 km^2 of land is destined to be urbanized, 0.912 km^2 will be expanded for tourism and 2.389 km^2 will be devoted to agricultural land (Ávila-Akenberg, 2002). These expansions should not be allowed to transgress into a conservation zone, but they have. In agricultural and grazing zones, soil conservation practices are non-existent and land plots are located in areas with steep slopes (PUMA, 2009). Human settlements constitute a major source of erosion and surface runoff because they often result in the removal of vegetation (Hupp et al., 2013). Variations in vegetation cover and land use are related to soil, weather, and the region's capacity to provide ESs (Yapp et al., 2010). Presently, the sub-basin shows low levels of erosion because minimal land use changes have occurred and hydraulic structures are limited. The good condition of these ESs has a strong influence on water quality; vegetation cover, soil conditions and soil-associated microorganisms in the sub-basin act as primary barriers to nitrogen and phosphorus enrichment (Quijas and Balvanera, 2014).

Another hydrologic service provided by the sub-basin is flood control; however, this service was not measured and is provided mainly by flood regulation structures in the upstream section of the sub-basin rather than natural factors. In this section, there are a large number of gabion dams, which have a negative effect on habitat fragmentation at the origin of the lotic system.

5.3. Biodiversity: supporting services

Habitat diversity and organisms. The macroinvertebrates and macroalgae communities in the Magdalena–Eslava River sub-basin have a complex structure, with clear differences in the relative influence of environmental conditions and spatial processes on the river community's composition. The volume and velocity of water flow sculpts the physical habitat of rivers by shaping the size of sediment particles, substrate type, stream geomorphology, and distribution and cycling of nutrients. These forces effect change by intervening in the water column and substrate layer in various ways. Consequently, it is possible to identify morphological and functional patterns that are shared among aquatic systems in different habitats (Kang and Kazama, 2014). The convergence of habitats occupied by different aquatic organisms resulting from evolutionary ecological processes may be largely related to the development of similar adaptations to maintain position in fast currents. Small organisms with reduced height have flexibility and the ability to bend the body in the direction of the flow. An example is found in elongated algae, which have thin and flexible structures, such as the lamina of *Prasiola mexicana*, mucilaginous colonies of *Nostoc parmeliodes* and *Placoma regulare*, and filaments of *Vaucheria bursata* that grow on steep inclines and banks of stable riverbeds where the current velocity is high (e.g. M-CS-1, M-CS-2, E-CS-1, E-CS-2). Bending of the body in response to the current can also be found among benthic macroinvertebrate families, including some Chironomidae and most Simuliidae. Most Simuliidae modify the position of their filtering fans to increase their food-gathering capacity and reduce the drag force of the current. Additional adaptations that allow river organisms to withstand the force of the current include size, hydrodynamic body shape, and the presence of anchoring and counterweight structures. The diversity of aquatic organisms in these rivers can be attributed to the diversity of habitats to which they are adapted. Of the organisms inhabiting a particular ecosystem, feeding patterns and trophic level status can serve as a reliable indicator of ESs. Therefore, loss of species sensitive to stream alterations can be a measure of existing or impending river degradation (Tetzlaff et al., 2005). For cyanobacteria, local environmental variables (e.g., temperature and total nitrogen) have an exclusive influence on the community composition, with no significant effect related to spatial distance. The community composition of Chlorophyta and Heterokontophyta was explained by variations in local environmental characteristics (e.g., temperature and discharge flow), with no significant effect related to spatial distance. In general, these macroalgae groups have strong dispersal mechanisms over long distances (Kristiansen, 1996; Branco et al., 2014). The relative contribution of macroinvertebrates families to ESs in the Magdalena–Eslava River sub-basin can be ascribed to the differences in the ecological features of each group. The heterogeneity of the habitat, discharge flow and nutrients also play an important role in biotic interactions and dispersal mechanisms therein, which can be seen in the heterogeneous composition of organisms (Heino and Mykrä, 2008). For example, in fluctuating environments such as the Eslava River, generalist species such as *Trichoptera* are typically present because they tolerate frequent variations in water flow (Merritt et al., 2008).

Providing that dissolved oxygen conditions remain favourable, the heterogeneity of low- or no-flow habitat zones, such as behind obstructions, leads to the creation of important havens for macroinvertebrates and macroalgae and critical microenvironments required for the reproduction and survival of vulnerable life stages (Bojorge et al., 2010). Aquatic organism diversity and its relationship to suitable habitat is determined by substrate heterogeneity, the level and regulation of flow, and the condition of the riparian vegetation providing shade and inputs of terrestrial plant organic matter to the water (Pert et al., 2010; Kang and Kazama, 2014). The above combination of physical, chemical and biological factors explains the differences in macroinvertebrate and algal diversity among sample stations. Diversity in hydrological conditions can explain survival rates of macroinvertebrates, as there is a correlation between the hydrological environment and taxa diversity (Kang and Kazama, 2014). It is important to point out that in mountainous rivers, diversity values tend to be lower than in tropical ecosystems (Bojorge et al., 2010). This pattern may be an outcome of the biological adaptations to this environment.

An overview of the quantity and quality of HESs provided in the sub-basin is provided in Table 4. The magnitude of the water yield ES function obtained in this assessment indicates a negatively impacted ES within the lower sub-basin. This condition is a consequence of human activity. Other HESs, including the regulation of water quality, hydraulic erosion, and sediment transport, appear to be in good condition. With respect to habitat and aquatic organism diversity, the middle section had the lowest values and would require an intervention to ensure the maintenance of beneficial habitat conditions and diversity. The data indicate that the headwater streams provide the highest number and quality of HESs in the sub-basin.

Table 4
Actual status of hydrological and biological indicators and their relationship with ecosystem services potential in the Magdalena–Eslava Rivers sub-basin.

Sampling site	Number of associated SWAT micro-basins	Indicators of ES provided	Actual status	Signal potential
M-CS-1	9	Water yield	320 mm	+
		Water quality	1.5	+
		Habitat diversity	1.54	**O**
		Hydraulic erosion	0–50	+
		Sediment transport	Aa^{+}	+
M-CS-2	7	Water yield	172 mm	**O**
		Water quality	0.65	+
		Habitat diversity	1.85	**O**
		Hydraulic erosion	0–50	**O**
		Sediment transport	B	+
M-CS-3	1	Water yield	52 mm	**x**

(continued on next page)

Table 4 (*continued*)

Sampling site	Number of associated SWAT micro-basins	Indicators of ES provided	Actual status	Signal potential
		Water quality	0.99	+
		Habitat diversity	1.14	**O**
		Hydraulic erosion	0–50	+
		Sediment transport	B	**O**
M-CS-4	1	Water yield	52 mm	**x**
		Water quality	1.43	+
		Habitat diversity	2	**O**
		Hydraulic erosion	50–500	**O**
		Sediment transport	C	**x**
E-CS-1	1	Water yield	134 mm	**O**
		Water quality	0.16	+
		Habitat diversity	1.35	**O**
		Hydraulic erosion	0–50	**O**
		Sediment transport	A	+
E-CS-2	1	Water yield	42 mm	**x**
		Water quality	0.33	+
		Habitat diversity	1.15	**O**
		Hydraulic erosion	0–50	+
		Sediment transport	B	**O**
E-CS-3	5	Water yield	279 mm	**O**
		Water quality	0.46	+
		Habitat diversity	1.8	**O**
		Hydraulic erosion	50–500	**O**
		Sediment transport	B	**O**

(+) Good potential (O) Moderate potential (x) Poor potential.
Water yield (mm): $\geq$ 300 (+); 299–200 (O); $\leq$ 199 (x).
Water quality: FC/FE 0.7–2 (+); FC/FE 2–4 (O); FC/FE $>$ 4(x).
Habitat diversity (Shannon-Wiener index mean value for macro-invertebrates and macroscopic algae): $H' > 2$ (+); H'1–2 (O); $H' < 1$ (x).
Hydraulic erosion control (ton/ha/year) 0–50 (+); 50–500(O); 500–1100 (x).
Sediment transport (Rosgen's classification): Aa^{+}, A (+); B (O); C (x).

6. Implications for potential HES

The ecological health of rural–urban streams is negatively related to the amount and localization of urban land use inside and surrounding the sub-basin (Miltner et al., 2004). This relationship is due to the lack of attention given to the effects of hydrologic modifications and changes in land use on lotic communities. In general, the effects of land cover change on hydrologic process are not measurable until at least 20% of a catchment has been converted (Brauman et al., 2007). In this case study, 14% of the land has been converted to urban area, and the effects are visible, mainly because the sub-basin is small in size and the urban areas are completely covered.

Stream regulation through the modification of hydraulic structures affects regional hydrological function, and therefore potential water quality control and sediment and nutrient transport HESs, because the structures increase water retention time and result in related land use changes in a rural–urban setting. Such regulations, if not properly implemented, may lead to water mismanagement, as in the case of intensive groundwater exploitation, which has led to the sinking of the urban infrastructure. Better management strategies for the conservation of surface water sources are needed to prevent such mismanagement. Water flow control structures reduce the risk of flooding and negatively affect water quantity and quality regulation and sediment transport. Protecting natural hydrological regulation increases the possibility of the synergistic conservation of biodiversity and, therefore, the continuity of many ecosystem functions and the resulting HES potential (Pert et al., 2010). Furthermore, where there is a loss of biological taxa because of disruption in their life cycles, a negative ecological response can result. The system is resilient up to a point but is reaching its limits and has historically been mismanaged. The influence of this mismanagement can be observed in the middle section of the sub-basin, where the lowest diversity values are found. These low values may be the result of the accumulated effects of gabion dams located upstream. The continuity of the river system is recovered by reducing the differences in the physical environment (e.g., velocity, substrate diversity, etc.) between the upstream and downstream reaches surrounding the gabion dams (Kang and Kazama, 2014).

Aquatic biodiversity is one of the main HES indicators within the sub-basin, denoting the space and time over which ecological processes develop, both as a service itself and in terms of the region's natural and cultural heritage (Quijas and Balvanera, 2014). A habitat diversity analysis has demonstrated that aquatic organisms can also be indicators of ecosystem function, as their adaptations may reflect changes in water quantity, nutrients, sediment in suspension and ecological quality in general (Quijas and Balvanera, 2014; Caro-Borrero et al., in press). This diversity should be considered when monitoring HES potential under variable conditions, as it may reflect spatio-temporal changes based on factors beyond geophysical variables, such as in a peri-urban setting.

Fluvial geomorphology is another important factor to consider because changes in the biota are directly related to habitat distribution and heterogeneity, which in turn are related to changes in the river's hydro-geomorphology, especially at tributary junctions (Benda et al., 2004; Thorp et al., 2010). Fluvial geomorphology may be affected by water extractions upstream, necessitating the determination of water quantity at potential extraction sites without endangering the ecosystem's function and capacity for resilience.

Illegal urban settlements, grazing and agriculture in highly erodible zones also play an important role in affecting ESs (Neitzel et al., 2014).

The removal of native vegetation may trigger a change in ESs provided, as vegetation structure and its capacity to regenerate regulates the processes involved in the water cycle and has an influence on water retention, filtration, and aquatic diversity (Yapp et al., 2010).

Cultural services, which were not directly assessed in this sub-basin study, include scenic beauty, recreational areas, sports zones and religious rituals. These representative peri-urban activities are performed by a large urban population on the outskirts of a large city with more than 20 million inhabitants (Jujnovsky et al., 2010). The riparian vegetation in urban rivers is of great cultural and scenic importance because many vegetated areas have been lost (Radford and James, 2013; Yapp et al., 2010). These potential ESs are related to the hydrologic cycle and water quality. When they are reduced, cultural services are adversely affected. Unfortunately, a common policy in Mexico City has been to channelize and pipe urban rivers, as they have been considered dumping sites in the past and sewage flow has been mismanaged, resulting in negative public health impacts in a densely populated area (Mazari-Hiriart et al., 2014). Therefore, this sub-basin has the potential to serve as an example of how good management and the maximization of potential HESs in an urban-rural setting can change water management. The improved management strategies proposed here could then be applied in other emerging economies or developing nations.

This study provides an example of the utility of an ES framework in a peri-urban system and can serve as a practical guide to decision makers when designing policy. This study recommends a policy that would take into account sustainable practices for existing activities in the area. Such a policy would involve well-regulated fish farms, native fauna farms, and controlled tourism activities that minimize human impacts in the middle and upper sections of the sub-basin, which provide the most beneficial ESs. The goal would be to promote economic growth in the area without compromising the river ecosystem's sustainability.

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